Model for Sucker-Rod Pumping Unit Operating Modes Analysis Based on SimMechanics Library

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Abstract. The article provides basic information about the process of a sucker-rod pumping unit (SRPU) model developing by means of SimMechanics library in the MATLAB Simulink environment. The model is designed for the development of a pump productivity optimal management algorithms, sensorless diagnostics of the plunger pump and pumpjack, acquisition of the dynamometer card and determination of a dynamic fluid level in the well, normalization of the faulty unit operation before troubleshooting is performed by staff as well as equilibrium ratio determining by energy indicators and outputting of manual balancing recommendations to achieve optimal power consumption efficiency. Particular attention is given to the application of various blocks from SimMechanics library to take into account the pumpjack construction principal characteristic and to obtain an adequate model. The article explains in depth the developed tools features for collecting and analysis of simulated mechanism data. The conclusions were drawn about practical implementation possibility of the SRPU modelling results and areas for further development of investigation.

Keywords: SimMechanics, sucker-rod pumping unit, dynamometer card, wattmeter card, diagnostics

1. Introduction

While oil extraction by means of sucker rod pumps has been going on for a long time, and this extraction method is widely found across the world, however, research of sucker-rod pumping unit (SRPU) operating modes continues to be a big challenge. According to the existing rules of SRPU operation, the main tool of proper operational technical conditions control is dynamometry. Specialist-technologist is able to distinguish one SRPU fault or another by look of a dynamometer card. Accuracy of such diagnostics depended solely on the experience and attentiveness of the operating staff. Furthermore, another challenge is the necessity to install attached equipment (dynamograph) on the pumpjack, which is a labour-consuming procedure itself [1]. In addition, reliability of cables routing to the attached apparatus which placed at the pumpjack moving parts is principally cannot be high. Hence, the need for sensorless SRPU diagnostics tools. A correct model, which would be able to reflect the key SRPU working fault types, is needed to develop such tools.

The design of pumpjack mechanism is an oscillating crank drive of sucker-rod pumping unit. It comprises V-belt transmission, reducer and dual planar four-bar linkage. A connecting rod of the

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machine makes a non-linear movement, which complicates a calculating procedure of coordinates for all mechanism points at each time instant.

To facilitate the calculation of such mechanism it is better to use special application packages for mechanics modelling, in particular Simulink SimMechanics library from MATLAB software. Aside from a possibility to build of mechanic system of any complexity, further advantages for choosing such software are calculation accuracy improvement by greater account of bodies moments of inertia, possibility of choice between joints with any set of degrees of freedom, assignment different types of interaction of bodies, visualization of mechanism movements.

2. Model building

This article describes creation of the model of rear-mounted sucker-rod pumping unit SRPD8-3-5500 manufactured by the Ural Transport Machinery Plant. The overall scheme of its design is shown in figure 1.

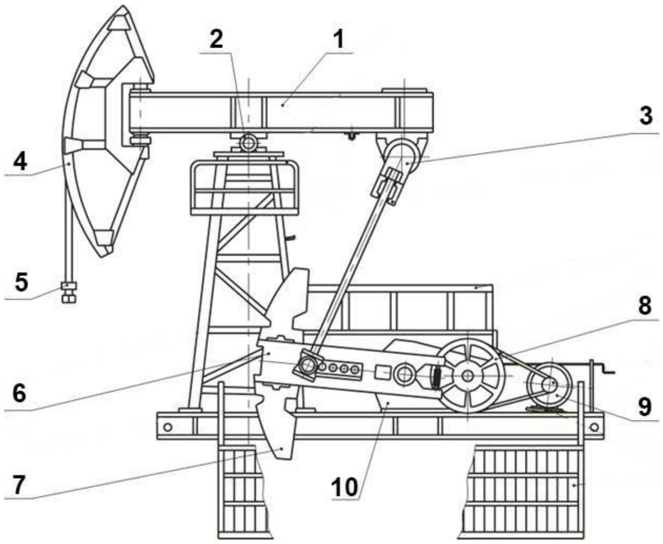

Figure 1. Overall scheme of sucker-rod pumping unit SRPD8-3-5500 design.

2.1. Frame

To simplify the model and to reduce calculation time it is sufficient to consider mechanism in only one plane. Machine model construction is performed using standard blocks from Simulink SimMechanics library. “Body” block is used to build the mechanism segments. These segments concern crank (6, figure 1), connecting rod (3, figure 1) and balance beam (1, figure 1). Section ends coordinates define the segment dimensions. Besides, coordinates of masses center, which may lie on both within and outside of the segment, should be specified. Two basic mass are considered – horse head (4, figure 1) and counterbalance (7, figure 1). The coordinate system is chosen according to conventional principle for this mechanism so the vertical axis Y is oriented through pressure and rotation point of balance beam (2, figure 1) and the horizontal axis X is oriented through crank (6, figure 1) rotation point. The pumpjack structure placed at the mentioned axes is shown graphically on figure 2.

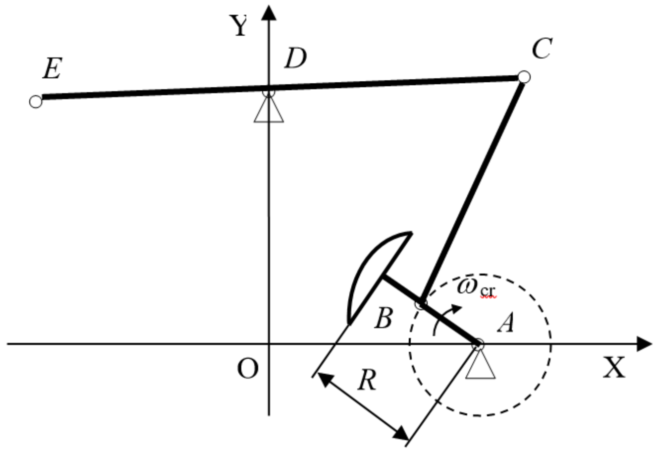

Figure 2. Design of pumpjack structure at calculation axes.

A SimMechanics model assembling begins with a “Ground” block, which is a stationary mount. “Machine Environment” block, which set out modelled environment parameters (one of which is the gravitational acceleration), is connected to the first used “Ground” block.

“Body” blocks are connected to “Ground” block and with each other by elements from “Joints” group, each with different degrees of freedom from absence in “Weld” block (strictly fixed connection) to six in “Six-DoF” block (rotational and translation for each of the three spatial axes). To set machine in motion, you should either attach “Body Actuator” block to a segment or attach “Joint Actuator” block a joint. The second option is more efficient because it ensures rotary motion around assigned axis. Blocks of pivot assembly type “Revolute” with one rotational degree of freedom were used to serve that purpose. These joints include pivot point of balance (2, figure 1), clamps of conrod (3, figure 1) and output shaft of gear reducer (10, figure 1). Z-axis, which is perpendicular to the mechanism plane, is chosen as rotational axis.

2.2. Reducer and V-belt transmission

The next model elements of no small importance are reducer and V-belt transmission (8, figure 1). They are simulated by “Gear Constraint” block which is imitation of two coupled cogwheels and its parameters is defined a desired gear ratio. At the same time, cogwheels are modelled by “Body” blocks as one point, which showcases a rotation center. In determining of their coordinates, it is essential that the distance between the rotation centers enable them to contact based on the configured “Gear Constraint” ratio. To simplify model at the present stage reducer and V-belt transmission are modelled only by common transmission ratio without giving consideration to backlash of gear and stretch of elastic transmission. The electric engine 4A200L6UZ drives the whole structure (6, figure 1). The engine model is defined based on induction motor equations written in common variables in a two-phase coordinate system, which stay fixed with respect to stator.

SimMechanics enables to display a graphic representation of a simulated object after a calculation is started which shows the visual picture of mutual location and motion of machine parts. figure 3, 4 and 5 demonstrate three mechanism conditions, which reflect all its key features: horizontal, upper dead center and bottom dead center. All other features will be considered below.

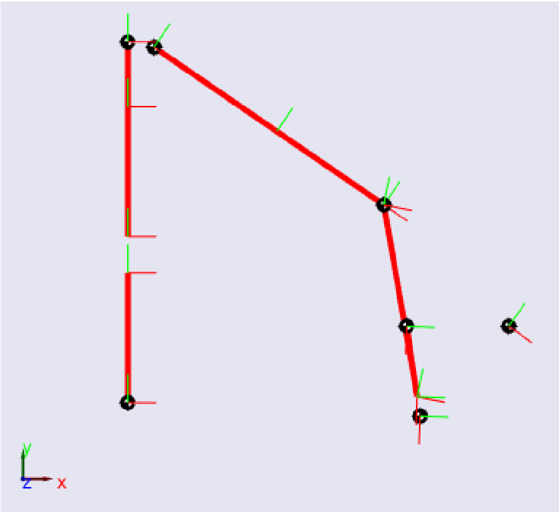

Figure 3. Horizontal state of balance beam.

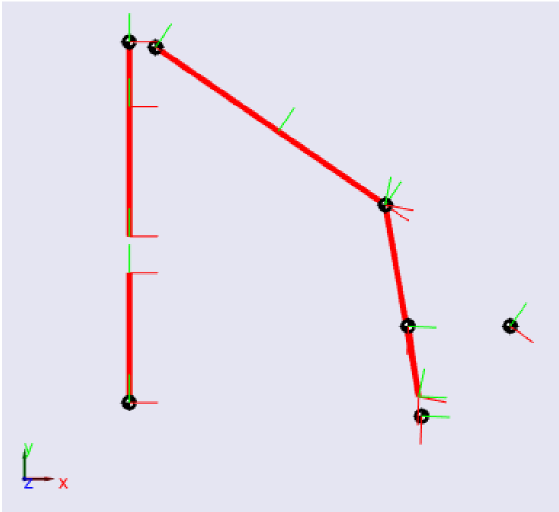

Figure 4. Upper dead center.

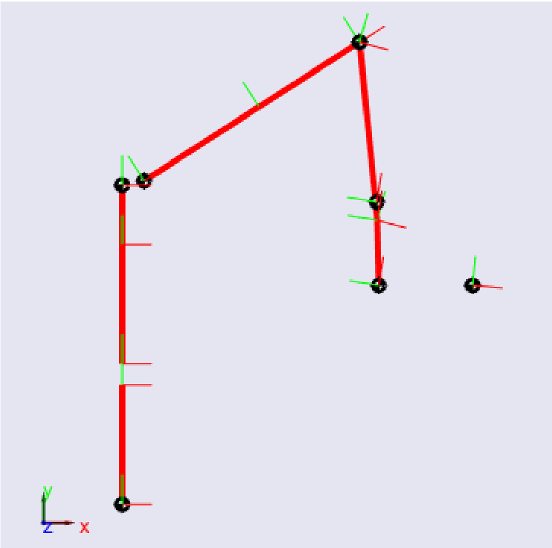

Figure 5. Bottom dead center.

2.3. Horse head

Now, let us move on to the horse head (4, figure 1) modeling that is integral part of any pumpjack construction [2]. A special form of horse head makes the polished rod hanging point (5, figure 1) moves with mechanism motion along the vertical line above well mouth, thereby avoiding skew and rubbing of the polished rod. The cambered horse head shape is circle segment with center in pivot point of balance and radius equal to the front side of balance. Therefore, balance horse head could be seen as a part of barrel, on which polished rod hanging ropes wrapped around during balance lifting and lowering. From this point of view, it is required to create flexible hanging using “Body” blocks of SimMechanics connected in chain to obtain circular arc while wrapped around a barrel. But this approach, firstly, is complicating the model, as far as a significant increase in number of elements is needed, secondly, has limited validity, because accuracy of circular arc approximation by sections depended on the sections amount. To avoid these problems, but at the same time save reliable information about a polished rod displacement another approach was embraced. Obviously, if one imagines horse head as cogwheel and polished rod hanging as pinion rack, then polished rod displacement would not be affected (if negligible elastic properties of hanging would not be taken into account) both vertically and horizontally (horizontal displacement is absent). However, standard facilities of SimMechanics does not permit to fulfil this interaction principle for blocks.

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Therefore, it was decided to adopt the equivalent solution and embody pinion rack as part of gear wheel with infinite radius. Of course, wheel has finite radius in the model, but its radius much bigger then balance front arm, in our case it is thousand times bigger. One issue with this approach is that polished rod hanging point will divert from vertical line above well mouth, though slightly but it gives rise to mistakes of model compilation. Therefore, hanging is connected with the point on the big wheel and polished rod by "Revolute" joint. To ensure the strictly vertical upward and downward movement of polished rod and sucker rod, there are connected by "Custom Joint" block, where the one progressive degree of freedom along Y-axis is defined. Although horse head itself is not shown on graphic representation of mechanism, however figure 4 and 5 indicates that in extreme balance positions polished rod and sucker rod keep their vertical position.

2.4. Sucker rod and plunger pump

The next step in model preparing is the imitation of sucker rod movement and plunger pump operation. Those processes are visually characterized by dynamometer card arranged as relation between force in polished rod hanging point and position of this hanging point [3]. Representative dynamometer cards obtained from model are presented in figure 6.

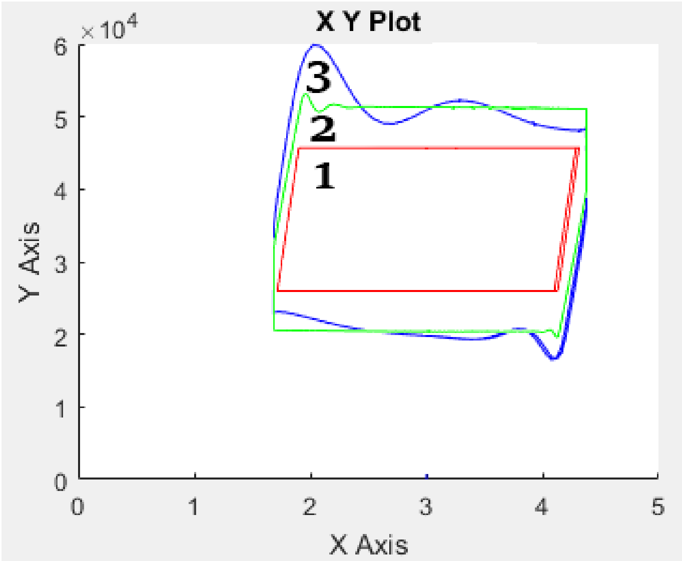

Figure 6. Representative dynamometer cards of plunger pump operation.

The submersible plunger pump operation is that the suction valve is open during upward stroke and pump receive fluid from the well, the discharge valve is open during downward stroke thus portion of fluid pushed up into the tubing string. Hence, polished rod force is equal to the sucker rod weight in fluid at the downward stroke and taken on additional weight of the liquid column above fluid surface in the well so-called dynamic fluid level at the upward stroke. Thus, polished rod force comprise sucker rod weight in fluid depending on the pump depths and liquid column weight depending on the dynamic fluid level.

Without taking into account features of valve group operation such as a sealing, incomplete closing and so on such load can be represented in model by variable mass which value is changed at the time of dead center passage and determined by specified pump depths and dynamic fluid level. That is why deep dynamometer card near pump plunger during normal operation under the assumptions is represented by rectangle whose height is determined by dynamic fluid level and width is determined by polished rod stroke length. From another observation point on the polished rod hanging, we see a rather different picture through expansion and contraction of the sucker rod during upward and downward stroke force in this point steadily increasing and decreasing, which is reflected in the inclined sections of dynamometer card (1, figure 6). A dynamometer card of static pump operation referred to as theoretical, because it does not take into account the dynamic and friction forces but it is a very important tool in dynamometry, which is able to evaluate a real dynamometer card.

To simulate action of elastic forces in sucker rod “Joint Spring & Damper” block is used, which is connected with “Custom Joint” block. Block parameters includes three positions: elastic modulus, damping coefficient and initial distance setpoint in not deformed condition (which is equal to zero if parts coupled).

Additionally, it is necessary to model the friction force arising between gland packing and polished rod. It is static friction in nature, which changes its sign during its passage through dead center. Herewith polished rod do not start a movement until tractive force is less than static friction that cause vertical section on the dynamometer card. Thereby specified conditions allow getting shape of dynamometer card shown on figure 6: on the full motor speed (3) and on decreased four times speed (2). Overall look of the obtained pumpjack model in SimMechanics is shown on figure 7.

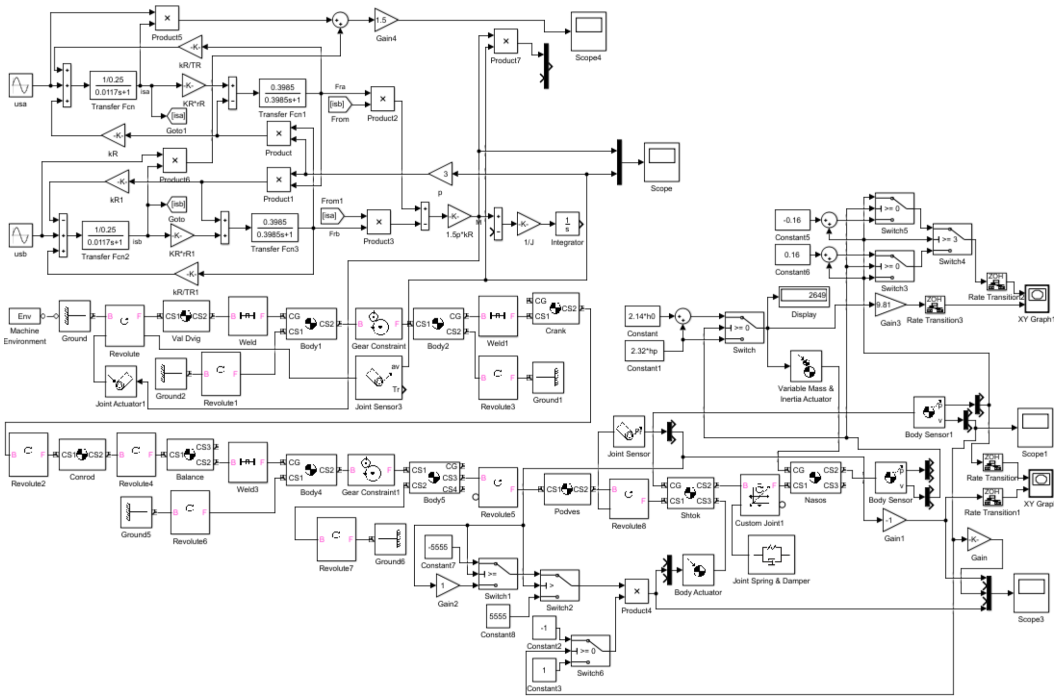

Figure 7. Overall look of pumpjack model in SimMechanics.

3. Simulation results

Simulation results has already partly been represented above since they were necessary for explanation of model structure. The most important and essential, of course, is dynamometry (figure 6), because it is general method of sucker-rod pumping unit diagnostics. Another important diagram of SRPU operation is wattmeter card (figure 8) of drive motor (relation between consuming electric power). Its advantage in respect to dynamometer card for diagnostics purposes is that wattmeter card might be obtained by standard tools without additional attached equipment and sensors [4]. However, it is more complicated for analytic processing and it is required development of algorithmic base. Such parameters as torque and speed of drive motor also available in the model (figure 9).

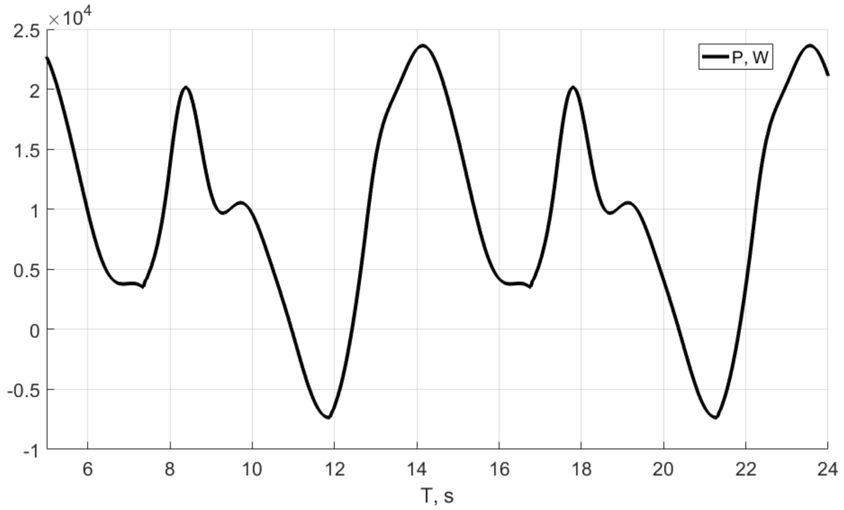

Figure 8. Wattmeter card of SRPU motor.

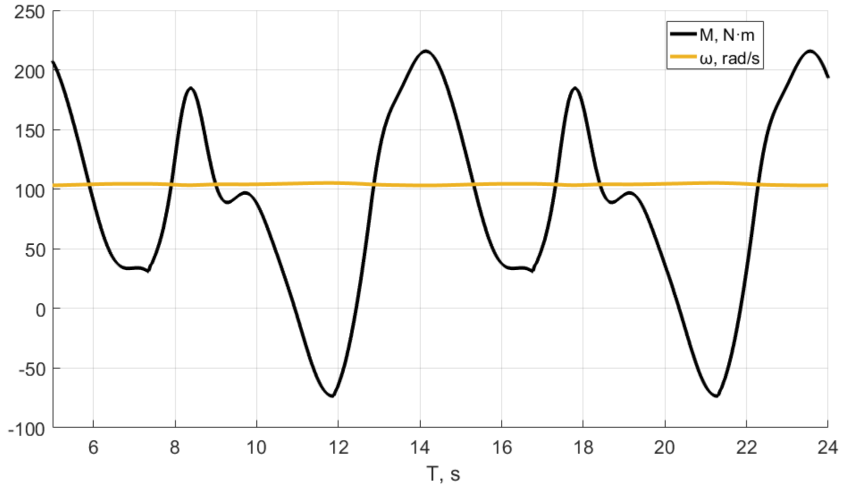

Figure 9. Torque and speed of SRPU motor.

4. Conclusion

Hence rather detailed model of sucker-rod pumping unit, which is satisfied to equipment diagnostics purposes, is developed. It served to simulate different typical faults of equipment to develop means and algorithms of revealing such faults without using of special sensors and external dynamometer systems. Several objectives of sensorless data acquisition such as dynamometer card, dynamic fluid level and downhole pressure are still promising for diagnostics and automated control purposes. Further efforts will be focused on design and improvement of model along these lines.

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